Alkali Metal Thermal to Electric Converter (AMTEC) Technology Development for Potential Deep Space Scientific Missions

by

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Abstract

This paper describes the alkali metal thermal to electric converter (AMTEC) technology development effort over the past year. The vapor-vapor AMTEC cell technology is being developed for use with either a solar or nuclear heat sources for space. This is a joint Air Force and NASA technology program. The Air Force is interested in converting solar heat to electricity at a very high efficiency, ~30%, with resistance to space radiation for Earth Orbital missions. NASA is interested in converting heat from a radioisotope heat source to electricity at very high efficiency, ~30%, to reduce the mass of the radioisotope material that has to be launched into space. The AMTEC technology is theoretically a very efficient converter. This effort is being conducted to reduce the theory to practice.

Two conceptual designs were prepared for a 100-watt electric power source that are compatible with either a solar or nuclear heat source. In parallel with the conceptual design effort, an experimental effort was conducted to build efficient AMTEC Vapor-Vapor cells based on past analyses and experiments with AMTEC power conversion technology. The AMTEC cells were designated PX for Pluto Express with the first experimental cell labeled PX-1, the second PX-2, etc. The ultimate goal was to design fabricate and test the first AMTEC ground converter system in a configuration determined by the conceptual design for either solar or radioisotope heat. Both conceptual designs had sixteen AMTEC cells for a 100-watt class power source. The design calculations predicted 100 watts at 28 volts with two 8-cell series strings connected in parallel. For the first ground converter system, it was decided to fabricate one series string of 8 cells and test them in a configuration that was prototypic of one half of one of the conceptual designs.

There were five different sets of PX cells, each with three or four different cells, i.e.; PX-4A, 4B, 4C etc fabricated and tested prior to building the AMTEC ground converter system. The last PX series was PX5. Each series of cells was improved over the previous series and the ground test cells were a result of the best of the PX-5 series. Two identical cells were fabricated and tested prior to fabricating the final cells for the 8-cell ground test. Then eight additional identical cells were fabricated and assembled into an 8-cell system and tested as the first AMTEC ground converter system. The significant results of the designs, the cells tests, and the 8-cell test are reported in this paper.

AMTEC Cell Operations

An operating schematic of the AMTEC Vapor-Vapor cell is shown in Figure 1. The vapor-vapor AMTEC is a thermally regenerated sodium concentration cell. The cell is a direct thermal energy conversion system with sodium evaporated at about 1 atmosphere of pressure, 1250 K, and condensed at 10^{-4} atmospheres of pressure, 625K, and pumped as a liquid from the condenser to the evaporator by a capillary wick. The high-pressure sodium vapor is transported through the Beta Alumina Solid Electrolyte (BASE) as sodium ions. Electrons are stripped off at a potential of about 0.3 volts, collected by a Titanium Nitride (TiN) cathode, conducted through a molybdenum screen to a load and back to the low pressure sodium vapor side of the BASE by a TiN anode. The sodium ions recombine with the electrons and leave the BASE as neutral sodium. The sodium condenses at the cold condenser and is pumped back to the evaporator by a capillary wick to repeat the cycle. This process has been fully described in the literature.[1]

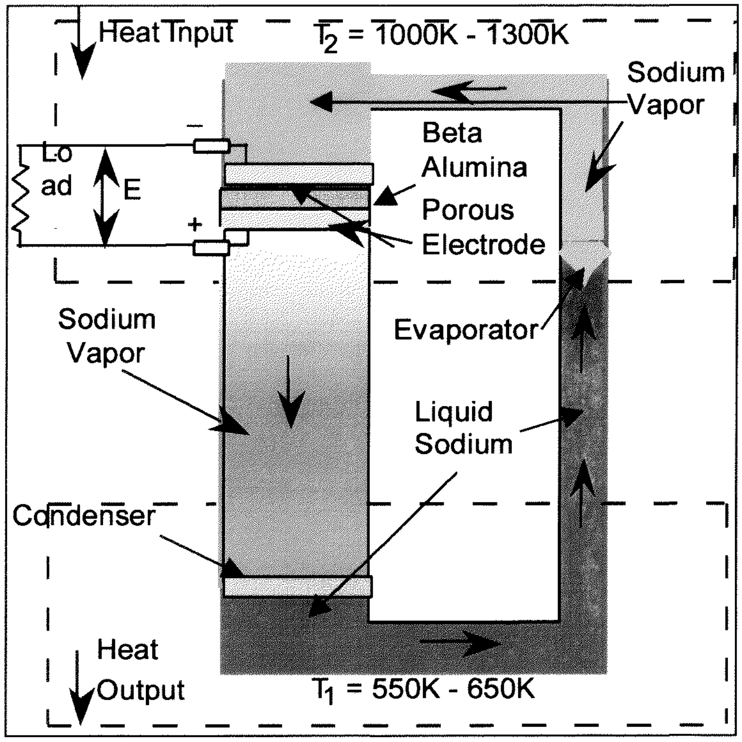

Figure 1. AMTEC Operating Schematic

AMTEC Cell Development

Advanced Modular Power Systems, Inc. (AMPS) under NASA and Air Force contracts in 1993 and 1994 developed the PL Series I cell. These AMTEC cells were single tube cells where many of the fabrication issues were developed and an efficiency of 18% was measured. The PL cell however only produced power at 0.5 volts and required hot feedthroughs to reach this efficiency level. The relatively low voltage made it difficult to meet system level voltage requirements, and the hot feedthroughs reduced the converter reliability. In 1995 a decision was made to adopt a multi-tube AMTEC cell as the baseline. The multi-tube cell program was designated PX Series II development. This was a significant step back in technology readiness level, but was judged necessary to meet mission voltage and reliability requirements.

PX Design Configuration

The conceptual design configuration[1] required all feedthroughs to be located in the cold end of the multi-tube cell with the BASE tubes near the heat source. The AMTEC tubes were to be connected electrically in series with a common high-pressure sodium vapor source. The sodium return artery and evaporator were to be located in the center of the tubes all in a cylindrical configuration. Heat shields were to be placed between the hot and cold end of the cell to improve efficiency. A picture of a seven-tube AMTEC cell with a central artery and evaporator prior to final closure is shown in Figure 2.

PX Design Issues

The main design issue was the location of the evaporator. The evaporator needs to be as close to the heat source temperature as possible to maximize the Carnot efficiency, but the BASE needs to be at a higher temperature than the evaporator to keep sodium from condensing inside the tube and potentially causing a short circuit of that tube. So the location of and the heat conduction path to the evaporator and the BASE tube with respect to the heat source are the most critical design issues. The heat shield design was the other critical issue. The heat shields are needed to prevent radiation loss from the hot BASE to the cold condenser while minimizing vapor flow pressure loss from the BASE exit to the condenser.

Design analysis predicted the evaporator would cool when drawing current and experience with other AMTEC cells indicated that placing the evaporator too close to the hot end could cause cell shorting at or near open circuit due to liquid inside the BASE tubes. So for PX 1A the evaporator was placed where it was calculated that the cell wouldn't short at open circuit. The evaporator temperature was measured to determine the amount of cooling at high current and a better location of the evaporator.

PX Series Design Strategy

The PX series was used to develop the multi-tube technology for maximum power and efficiency by analyses and experiments. Under an AMPS Air Force contract, with funding by Air Force and NASA and contract management by a technical team consisting of engineers from Air Force Research Lab, NASA Jet Propulsion Lab, NASA Lewis Research Lab, DOE Headquarters, DOE support contractor Orbital Science Corporation and AMPS, design changes were made based on experimental and analytical results. The cells were analyzed and manufactured at AMPS and tested at Air Force Research Lab, Phillips site. The general evolution and dramatic increase in power level from one cell over one year of development is shown in Figure 3.

PX-1A: The first test cell, shown in Figure 2, had 7 relatively short BASE tubes, with a 3 cm^2 electrode area, and copper current collectors. It had a conical evaporator, located as described in an earlier paragraph.

PX-1B: The measured evaporator temperature change during the testing of PX-1A was small and poor performance indicated that the evaporator needed to be closer to the hot side. The evaporator was moved closer by 0.635 cm.

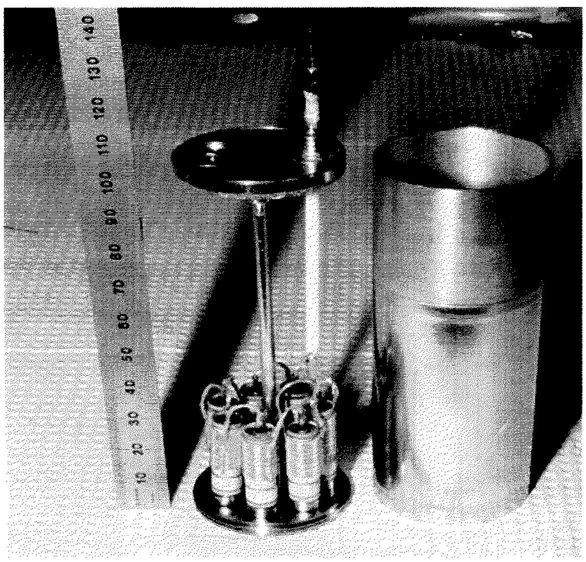

Figure 2. PX-1A Cell with 7 BASE Tubes

PX-1C: Test results showed that PX-1B performed better than 1A but still not as predicted. The expected evaporator temperature drop in 1B as the current was increased did not occur. Experimental data from AMTEC cell test indicated that the BASE tubes in 1A and 1B were not producing sufficient power. The BASE tubes were upgraded for PX-1C, heat shields were added and the evaporator location was not changed to compare the effect of the other changes to 1B. As shown in Figure 3 the power output increased from 0.5 watts to 1.5 watts.

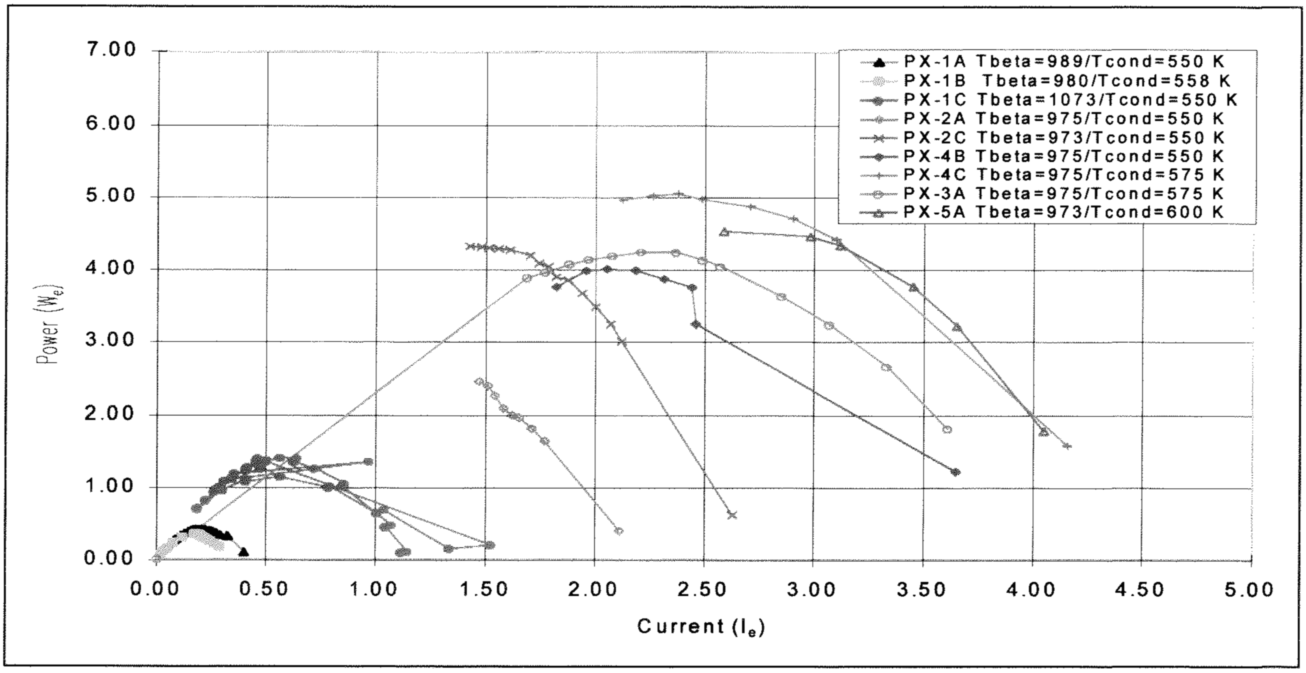

Figure 3. Measured Power (Figure provided through the courtesy of J. Merrill at Phillips Lab.

PX-2A: Insufficient power from PX-1 series and the lack of the evaporator temperature drop with high current indicated that the evaporator needed to be still closer to the hot side. The possibility of condensing in the BASE tube would be dealt with by limiting the current to the maximum cell efficiency operating point. The evaporator was located where it was predicted that the BASE temperature would be lower than the evaporator temperature at 2 amps of current. The chevron heat shield configuration was included in PX-2A and higher temperature braze material was used at the cold side feedthrough. The PX-2 cell is shown in Figure 4.

PX-2C: The PX-2A IV curves showed that the evaporator was located near the ideal location, so it was kept the same for PX-2C. Chevron and cylindrical heat shields were included in PX-2C. The power was 4.2 watts as shown in Figure 3.

PX-3A: This cell series was designed to be a 3.2 cm diameter cell rather than the 3.8 cm diameter of the other cell series. This series was out of chronological sequence and tested after the PX-4 series and at about the same time as the PX-5 series. The PX-3A cell was designed and fabricated by AMPS. This cell, shown in Figure 5, used 5 BASE tube assemblies. The smaller diameter made the fit between the cell wall and the heat shields very tight, as shown in Figure 6. Test data from this cell is shown in Figure 3, with a maximum power output of 4.2 watts from only 5 BASE tubes rather than 6 or7.

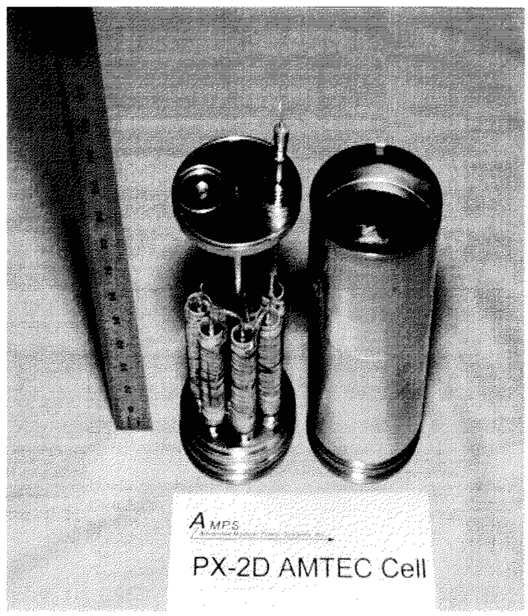

Figure 4. PX-2 Cell with 7 BASE Tubes

PX-3C: This cell was design by Orbital Science Corporation.[2] This design used a rhodium coating on the inside of a Haynes 25 material cell wall to reduce radiation losses, a modified hot end design fabricated from nickel, and a flat surface evaporator. All other cell designs used a conical evaporator.[1] The PX-3C cell was run very late in the development program. It did not produce the same power level as the PX-3A cell and is not shown in the performance plots of Figure 3.

Figure 5. PX3A Cell with 5 BASE Tubes

PX-4B: This cell was the first cell series with 6 BASE tubes for a better match to the heat flow from the radioisotope heat source, and molybdenum instead of copper current collectors for longer life capabilities. This cell performed moderately well, as shown in Figure 3, but had some compromises during the fabrication that reduced its power.

PX-4C: This cell was identical to PX-4B, except with improvements in fabrication and the evaporator was 0.19 cm closer to the hot end. This cell performed very well with maximum power of 5 watts at a BASE temperature of 975K, as shown in Figure 3.

PX-5A: This cell, shown in Figure 7, was identical to PX-4B, and was intended to be a final test before the fabrication of the cells for the 8-Cell system. This cell produced slightly lower power than 4C at the peak power point. At this time the cause is unknown.

PX-G: These cell were the first cell fabricated as an identical batch of ten cells. The results of the acceptance testing of these cells are reported in the literature.[3] Eight of these cells were installed in a system tested at the Air Force Research Laboratory, Phillips Site. The converter, shown in Figure 8, has operated for 2000 hours at a power output of 25 watts, shown in Figure 9, with system efficiency of 10%. Taking into account system thermal losses and the electrical interconnect losses; the cells are operating at 13 or 14% efficiency. At a hot side operating temperatures of ~1100K, this early demonstration test is exactly what is predicted. Future potential space power systems will be operated at a higher temperatures, higher powers and higher efficiencies.

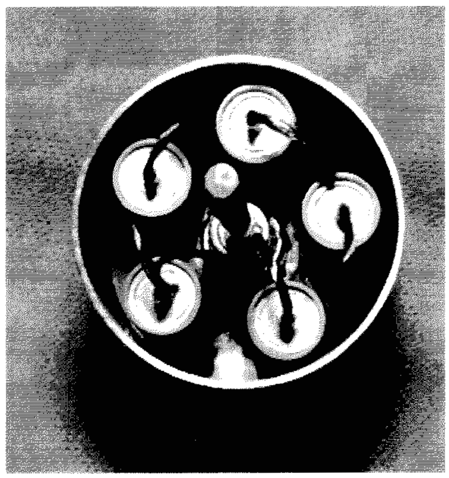

Figure 6. PX-3A Cell Top View

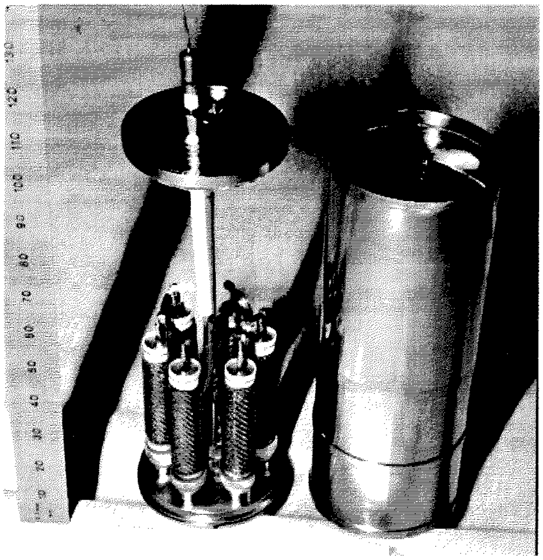

Figure 7. PX-5A Cell with 6 BASE Tubes

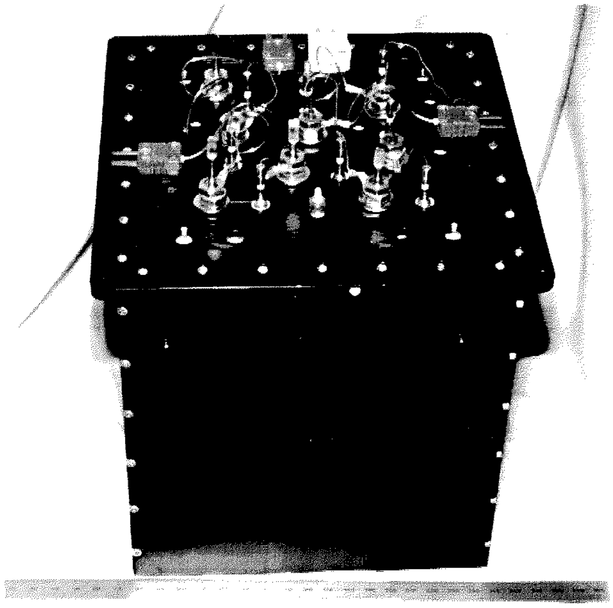

Figure 8. AMTEC 8-Cell Ground Converter Test Using PX-G Cells with 6 BASE Tubes

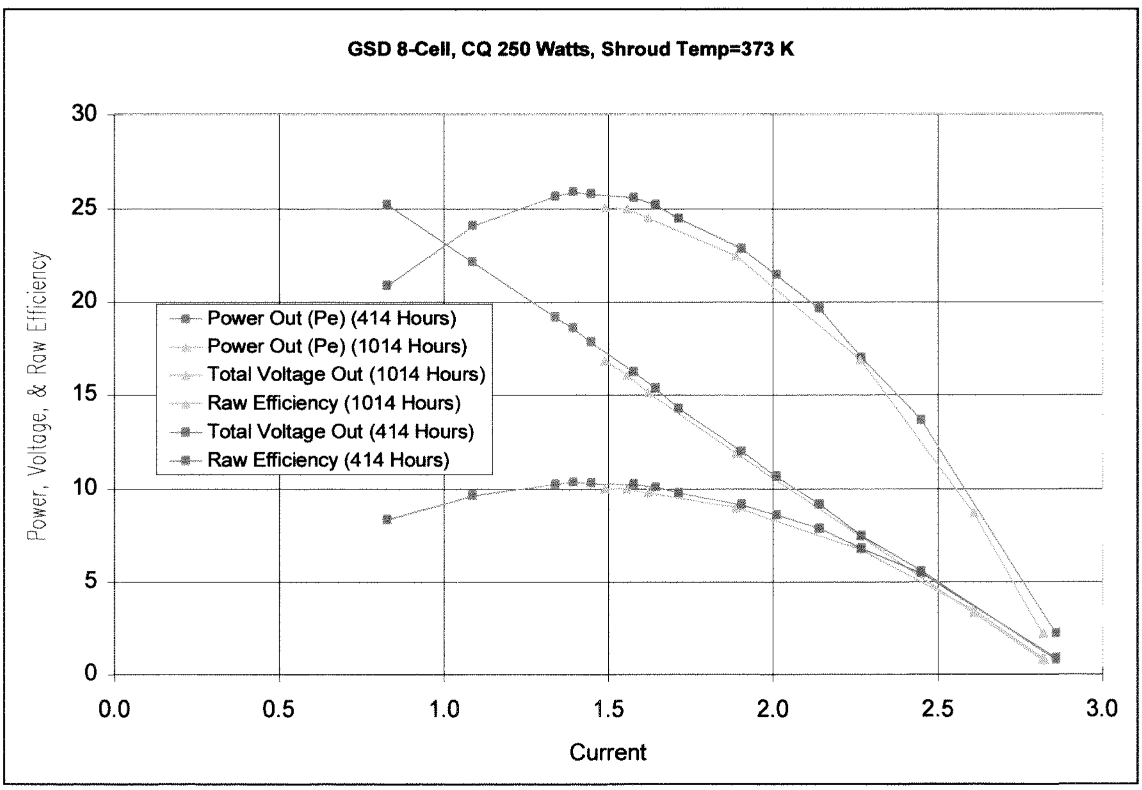

Figure 9. AMTEC 8-Cell Converter Performance (Provided by J. Merrill of Phillips Lab)

Conclusions

The PX series development of the Vapor-Vapor AMTEC cell was very successful as illustrated by Figure 3. In a one-year development time the power output form a multitube cell increased from 0.4 watts to 5 watts within the same volume. The first attempt to fabricate identical cells and test them in a prototype space configuration was also very successful. Two of the ten cells were fabricated and successfully tested. Then the next eight cells were fabricated, acceptance tested and assembled into the 8-cell ground converter system. This 8-cell converter system was shipped to Air Force Research Laboratory, Phillips Site and tested. The initial power output, with 250-watt thermal input, was 26 watts at 18 volts. The power output degraded over the first 500 hours to 25 watts at 16.7 volts, has remained steady for greater than 2000 hours and is continuing to operate at 25 watts output.

Acknowledgments

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References

1. R. K. Sievers, J. R. Rasmussen, C. A. Borkowski, T. J. Hendricks and J. E. Pantolin, "PX-5 AMTEC Cell Development," Proceedings of the Space Technology and Applications International Forum, January 26 – 29, 1998, American Institute of Physics, NY, STAIF-98, CONF-980103.
2. A Schock, H. Noravian, V. Kumar and C. Or, "Effects of Design Variations on AMTEC Cell Efficiency, and of Operating Parameters on Performance of OSC Cell Design," Proceedings of the Space Technology and Applications International Forum, January 26 – 29, 1998, American Institute of Physics, NY, STAIF-98, CONF-980103.
3. M. E. Carlson, J. C. Giglio and R. K. Sievers, "Design And Fabrication Of Multi-Cell AMTEC Power Systems For Space Applications," Proceedings of the Space Technology and Applications International Forum, January 26 – 29, 1998,American Institute of Physics, NY, STAIF-98, CONF-980103.